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Send in the 'Bots

Taking Dangerous Positions

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In a hostile future, we'll recruit machines to perform work too dangerous for humans. Across a landscape contaminated by radiation, biological warfare, or chemical spills; in an earthquake area rippled by aftershocks; through a raging inferno, a minefield, a crossfire zone — robots, those intelligent, agile, and fearless creatures, can go in and get the job done.

Backpack-sized robots ("packbots"), carried to the scene by individual soldiers or emergency personnel, cannot transport all the mission payloads that might be necessary to investigate an area of interest. For example, one robot might have several perceptory sensors such as cameras and lidar scanners for mapping. Another robot might wield a manipulator for opening gates or doors. So researchers have developed the "leader/follower" concept: one robot traces out a safe path via user control and autonomous navigation. Then other robots can be sent along the same path using the leader/follower behavior. The lead robot robot can also be told to "follow" its own path backwards to effect a retro-traverse.

Leader and follower robots use, of course, GPS to plot their way *into and out of danger.*

The Tactical Mobile Robot program in the Defense Advanced Research Projects Agency (DARPA) Advanced Technology Office has enlisted Jet Propulsion Laboratory's (JPL's) Machine Vision Group in leading the design and implementation of its perception urban robot. This urban robot — Urbie — is a joint effort of JPL, iRobot Corporation, the Robotics Institute of Carnegie Mellon University, and the University of Southern California Robotics Research Laboratory.

Urbie's initial purpose is mobile military reconnaissance in city terrain, but many of its features will also make it useful to police, emergency, and rescue personnel. Rugged and well-suited for hostile environments, its autonomy lends Urbie to many different applications. Such robots could investigate contaminated environments or assist in search and rescue in earthquake-struck buildings and other disaster zones.

The Urban Robot platform developed at JPL is a novel chassis populated with several different software-controlled cameras and sensors. This combination creates a robot that can autonomously operate in widely varying terrain and can investigate different environments that are dangerous to people.

The basic chassis is a tracked vehicle capable of up to 2 meters/second movement over rough terrain. The chassis carries many sensors and two processors for vision processing and robot control.

The robot's arms rotate 360 degrees and they make the body very adaptable. They can help the robot mount obstacles or stairs, and they can flip the robot over if it becomes inverted.

Measuring 60 x 50 x 17 centimeters and weighing 20 kilos, Urbie can be carried to any location for deployment. It can also investigate areas too difficult for humans to probe, such as culverts and tunnels.

Sensors. Urbie carries, among other specialized equipment, stereo cameras, an Omnicam, three-axis gyros and accelerometers, a digital compass, and a high-precision GPS receiver. In the future Urbie will also carry a night-vision camera and a two-axis scanning laser rangefinder.

The laser rangefinder, a new sensor developed at JPL, is light and small enough to be fit onto a small mobile robot and provides the capability to collect 3-D range data of the environment, for 3-D mapping, obstacle avoidance, and terrain mapping.

The Omnicam is a 360-degree field-of-view camera that takes images of the full environment around the robot in a single exposure. Software unwraps the raw circular image into a panoramic view. On-board software algorithms and a remote human operator then use this unwarped image to see all the way around the robot.

The night-vision camera will enable robot operation in darkness and in dimly-lit indoor environments.

'Bot Navigation

The need for multiple robots raises the problem of how to navigate them from the departure point to the objective with minimal burden on the human operator. Operator involvement is necessary to designate waypoints and intermediate objectives for the first robot; however, it is desirable for the rest of the robot team to automatically follow the path of the leader, without necessarily maintaining visual contact with each other.

Prior work on robot leader/follower behavior has taken several approaches, including visual motion tracking of the lead vehicle and using inertial navigation systems (INS) combined with GPS to record the path of the leader, which is then traversed by the follower using the same sensors. Methods depending on visual contact do not meet the requirements of movement through obstacle-laden terrain. Prior path-following work based on INS/GPS has all been done on much larger platforms.

Hence, one of the main challenges for packbots has been to identify a sensor suite that would enable path-following within the size, weight, power, and cost envelope of our vehicles.

Other challenges include coping with GPS dropouts in urban areas and under tree canopies, coping with obstacles that fall within the positional uncertainty of the path-following system, and enabling path-following through constrictions that require greater positional accuracy than is available from the INS/GPS sensors, for example, following a path through a culvert.

The JPL Machine Vision Group has developed a leader/follower system that addresses all of these challenges, with a path-following system based on Kalman filtered IMU, differential GPS, compass/ inclinometers, and wheel-encoder data (see Figure 1). The system avoids obstacles with an arbiter-based architecture that combines steering votes from the path-following behavior with steering votes from a stereo vision-based obstacle avoidance behavior. The team is currently extending this system by

• using optimal smoothing of the leader's path to reduce the impact of GPS dropouts

• developing specialized feature recognition and tracking algorithms to guide the followers through constrictions such as doors and culverts

• developing more general outdoor mapping and landmark recognition capabilities to further reduce the reliance on GPS.

Navigation Sensors

The primary constraints for the navigation payload are accuracy, size, and power: the sensors must fit within the space and power budgets afforded by the chassis while delivering the resolution to reliably determine the position of the robot. As an autonomous platform, the packbot carries all perception, computation, and power resources onboard in roughly 13,000 cubic centimeters of contiguous payload space.

A 20-cell NiCd battery pack provides a total energy storage of 120Wh. Power consumption with the robot standing still is approximately 75W, and the power required for driving varies with the terrain.

The robot and all subsystems must be able to survive the shock of being thrown or dropped modest distances.

Accuracy Requirement. Autonomous path-following and path-generation require that both the leader and the follower have tight control over their respective positional accuracy. The accuracy of the sensor directly limits the ability to follow a path precisely. The terrain and the follower's level of autonomy dictate the accuracy limit and resolution. If a follower must blindly weave through a series of tightly-spaced obstacles such as trees, then the accuracy of the estimated position must be high — roughly half the width of the robot, or 25 centimeters. On the other hand, if a reactive follower weaves through the same obstacles, the accuracy requirements can be relaxed.

To meet the requirements of operating in such varied and unstructured environments, Urbie uses a combination of GPS and inertial sensors. GPS information is used in clear and unobstructed outdoor areas while inertial sensor data augments GPS in areas with poor or no reception such as urban canyons, under tree canopies, or indoors.

Using a differential base station to provide corrections increases positional accuracy by an order of magnitude. Operation in real-time kinematic (RTK) mode increases resolution by another order of magnitude. The research and development team opted to have both these features. The base-station is connected to Urbie's operator interface laptop, which sends the differential updates through the connection to the robot. Then the robot processor passes the corrections down to the card for use.

Position Estimation

Precise localization is one of the main requirements for the task of autonomous path-following. The differential GPS (DGPS) onboard the Urbie packbot provides position estimates with 2–20 centimeter uncertainty under favorable conditions. These uncertainties can become much higher when operating near buildings or trees, which occlude satellite signals, making GPS navigation unreliable.

During GPS dropouts, the system must appropriately combine signals from the inertial sensors, compass/inclinometers, and motor encoders to determine the robot's location until the next GPS update. By integrating accurate estimates of its linear and rotational velocity ,the packbot could potentially track its position for a long period of time. As the robot turns using skid-steering, the inherent slippage makes the estimates based the motor-encoder signals untrustworthy, especially those regarding rotational velocity. Since even small errors in orientation can cause large errors in position, the team focused on deriving precise heading estimates, using three gyroscopes in an orthogonal conguration. Integration of their signals provides estimates of the roll, pitch, and yaw angles determining Urbie's attitude.

System Architecture

Device drivers manage the navigation sensors by passing data through a software message queue to a single software task that carries out the necessary calculations. This task runs the Kalman filter and position-estimation algorithms after each piece of sensor data arrives. It then updates the robot's current state in a shared memory space where other tasks can access it. Currently GPS determines the robot's position both for recording and following paths. When the robot is indoors, or when it drives into GPS-dropout areas, the position estimation is calculated with a simple interpolation using the Kalman-filtered heading and a raw odometry estimate from the wheel encoders.

The path-recording and path-following code and other software tasks can access the latest robot position and orientation estimates at variable rates and make decisions accordingly. A software task monitors current position and records a 3-D point after a certain constant offset has been passed, forming the robot's trail from successive points.

The robot's trail is accessed, downloaded, and then edited using a graphical user interface running on a laptop used to control and test the packbot. The modified or whole trail is sent to another robot or back to the same packbot, which accepts the trail, passes it to the path following module, and begins driving with a "go" command.

Robert Hogg *is a researcher at the Jet Propulsion Laboratory, California Institute of Technology. This story draws extensively from his paper "Sensors and Algorithms for Small Robot Leader/ Follower Behavior," co-authored with Arturo Rankin, Michael McHenry, Daniel Helmick, Charles Bergh, Stergios I. Roumeliotis, and Larry Matthies, first appearing in proceedings of the International Society for Optical Engineering (SPIE) 15th AeroSense Symposium. For the full paper, see http://robotics.jpl.nasa.gov/ tasks/tmr/papers/homepage.html.*

Manufacturers

The packbot is built upon the Urban II platform developed at iRobot Corporation (Somerville, Massachusetts). It uses the NovAtel (Calgary, Alberta, Canada) Millenium RT-2 receiver, BEI Systron Donner (Concord, California) gyroscopes and TCM2 compass/inclinometers from PNI Corporation (Santa Rosa, California).